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IMPROVED ENGINE PERFORMANCE AND EFFICIENCY UTILIZING A SUPERTURBOCHARGER

Thomas Waldron
Ed VanDyne
Jared Brown
VanDyne SuperTurbo Inc.
Fort Collins, CO

ABSTRACT

The need for current and future military vehicles to include more powerful and efficient powertrains is critical to both improving operational performance and reducing logistical burden. VanDyne SuperTurbo Inc. is working jointly with TARDEC and OEM partners to develop and field a revolutionary technology that simultaneously increases available engine power and reduces overall fuel consumption. The ability to incorporate efficient supercharging will allow vehicles to accelerate faster in combat situations and accept a heavier load. The ability to mechanically recover waste heat energy will allow vehicles to improve their operational range and reduce the Class III supply chain. SuperTurbo technology additionally reduces visible soot emissions and is transferable to gensets and other equipment. The end result of fielding this kind of capability will be a force protection multiplier that equips the warfighter with better performing systems.

INTRODUCTION

VanDyne SuperTurbo is an innovative company that is developing a unique solution to the challenges facing future internal combustion engines. SuperTurbo technology combines the capability of a supercharger, turbocharger and turbo-compounder in one single device. This is accomplished by mechanically controlling the speed ratio between the engine and the turbine/compressor wheels. Key to the technology is a proprietary high speed drive system that allows for reliable and efficient torque transfer on and off the high speed rotating parts. When combined with a continuously variable transmission (CVT), it becomes possible for the engine management system to command a desired boost pressure at any engine operating condition.

Traditional superchargers are excellent at providing low end torque, rapid load acceptance and quick transients. However, superchargers receive all their power from the engine and are thus a parasitic drag, resulting in decreased overall engine efficiency. The VanDyne SuperTurbo overcomes this by supplying ultra efficient supercharging air flow. Since the turbine is constantly collecting waste heat energy from the exhaust, the SuperTurbo only requires the engine to supply enough power to make up the difference between requested compressor power and available turbine power. The SuperTurbo also employs a centrifugal compressor, which has greater efficiency than traditional roots compressors.

While performing as a supercharger, the direction of torque is flowing from the engine to the SuperTurbo. However, at highway cruise conditions and higher speed/load points, the turbine collects more energy than is required by the compressor. When the turbine power exceeds the requested compressor power, the direction of torque reverses and the power is compounded back to the engine. This is made possible by a high efficiency turbine wheel. Normal turbochargers must balance the turbine power against the compressor power, taking into consideration the lag induced from inertia and the possibility of overspeed. The SuperTurbo turbine is not encumbered by these restrictions, and thus can be optimized to collect the greatest amount of exhaust heat energy.

The VanDyne SuperTurbo provides an additional variable for engineers focused on performance and efficiency. The ability to command an exact level of air flow, without large parasitic losses, allows for a degree of combustion control flexibility that has never been previously available. The SuperTurbo's ability to affect both exhaust pressure and intake pressure also facilitates a variety of emission strategies.

Any successful engine downsizing strategy relies on ensuring the drivability and performance of the vehicle. The SuperTurbo's ability to increase available torque through efficient supercharging fits perfectly into an engine

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downsizing or down-speeding approach. Any successful fuel efficiency strategy includes minimizing engine losses and recovering as much available energy as possible. The SuperTurbo's ability to collect extra waste heat energy and mechanically transfer it directly to the engine fits perfectly into all fuel economy development programs.

VanDyne SuperTurbo Inc. is currently in the final year of an SBIR Phase II with TARDEC, with the stated goal of increasing fuel efficiency for the U.S. Army's Heavy Equipment Transport (HET-A1). The modeling program demonstrated the SuperTurbocharger's ability to both improve fuel efficiency by over 5% as well as increase the total available engine power by over 14%. The program has passed the critical design review (CDR) and prototypes are currently being built for testing. With modeling, engineering and material support from Caterpillar, the program is now progressing to laboratory testing at TARDEC.

PROGRAM DEFINITION

The purpose of this Small Business Innovative Research (SBIR) Phase II Contract is to further elevate the SuperTurbocharger to Technology Readiness Level 6 (system and sub system prototype demonstration in a relative environment).

The goal of this effort is to build a compact, lightweight SuperTurbocharger and compare it against the currently used turbocharger in military vehicles to evaluate the impact on performance and efficiency.

Objectives:

- Design and fabricate full-scale SuperTurbocharger
- Test the baseline engine with and without the SuperTurbocharger and compare results against each other as well as to the theoretical model
- Develop vehicle integration and production cost structures of the SuperTurbocharger technology

Figure 1: HET-A1

SUPERTURBO DESIGN

The SuperTurbocharger has been developed by VanDyne SuperTurbo specifically for more efficient exhaust heat recovery to improve fuel productivity. The device consists of a high speed planetary step down mounted on the same shared axle between the turbine and compressor. The high speed planetary provides the speed reduction necessary to reach CVT operating speeds. The CVT allows for bi-directional torque transfer and overall ratio control.

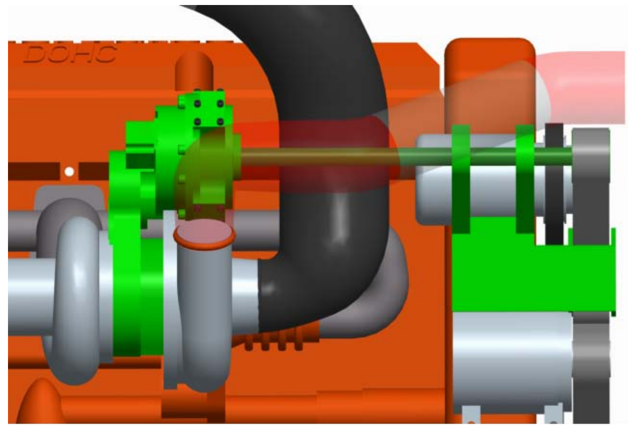

Figure 2: Side view of installed SuperTurbo

Figure 2 shows a diesel engine installation with the CVT positioned above the high speed planetary. This configuration is usually required due to vehicle frame rail interference. This example shows power transfer from the engine occurring at the belt drive, however repositioning of the system allows for interface with flywheel PTO is another alternative.

Figure 3: 2nd generation automotive SuperTurbo

Figure 3 is an example of a small automotive gasoline SuperTurbo that can operate up to 240,000 rpm. The design of the fixed ratio planetary is adapted based upon several factors, including: total ratio required, surface velocity at each power transfer point, torque required at each power transfer point, allowable parasitic losses, expected system life, overall size and packaging. The planetary designs are chosen from available gear and traction drive designs, or a combination thereof. VanDyne has developed proprietary techniques to implement active and passive loading and control systems that allow the high speed drive to appropriately balance efficiency, performance and durability.

Figure 4: Current generation large diesel SuperTurbo

Figure 4 shows a current generation large SuperTurbo installed on a diesel engine. Current large diesel designs range from 7 to 18 liters in engine displacement. The photo shows the custom designed turbine (and scroll) on the left, connected through the planetary drive over to the compressor. The CVT is positioned behind the intake, and in this installation connects to the crankshaft belt drive.

VanDyne has both internal CVT designs and established current suppliers. The selection and integration of the correct CVT is based upon a variety of factors, including: ratio range, input/output torques, input/output speeds, shifting rate, packaging, durability and specific efficiencies at targeted operating conditions. The complete system seen in Figure 4 is fully functional and currently in durability testing. The fundamentals for the Army SuperTurbo program are not significantly changed from the current large diesel programs.

The Custom Turbine Design

The custom turbine is an essential part of optimizing the mechanical turbo compounding capability of the SuperTurbocharger. In order to maximize the heat recovery from a selected engine and/or application, the SuperTurbocharger turbine needs to be customized. VanDyne has spent the last year creating a designing method that produces turbines specifically to operate at efficiencies greater than 80%. In a standard turbocharger, the compressor and turbine performance maps need to be balanced with each other. Additionally, traditional turbochargers utilize waste-gates or VGT systems to prevent overspeed. However, the turbine and compressor connection with the CVT within the SuperTurbocharger makes it possible to change that paradigm. Figure 5 shows the difference between the traditional and SuperTurbo turbine designs.

Figure 5: A comparison between the stock turbine design and the SuperTurbo design

In essence, the turbine is designed to collect the greatest amount of waste energy at desired engine operating points with no need for a waste gate. The energy that is now collected is significantly more than the compressor needs to provide the desired boost pressure. As the CVT transfers the excess energy collected to the crankshaft, the stress on the compressor and turbine is reduced. Figure 6 is one turbine map custom designed by Dr. Schumacher (VanDyne chief scientist and turbine aerodynamic expert) for use in the Army SuperTurbo. The map shape and efficiency bands are

demonstrative of what is possible given the SuperTurbo's unique characteristics.

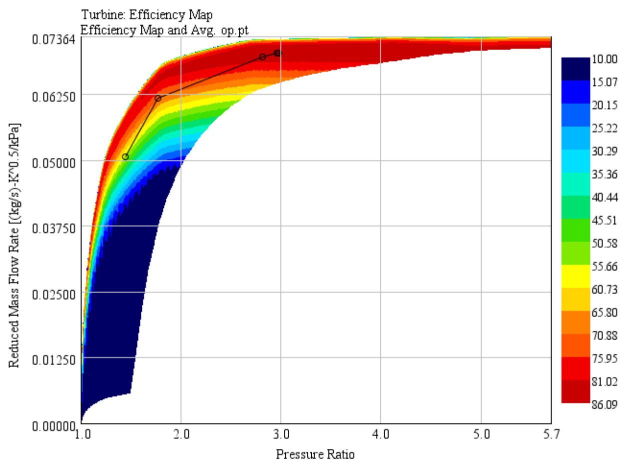

Figure 6: Schumacher turbine map

MODELING RESULTS

The following results summarize the BSFC improvement of the stock engine against one equipped with the SuperTurbocharger. Initial program discussions identified that the HET was having particular issues during desert operations under higher loads. VanDyne designed the turbine to optimize around the B100 operating point, which is seen at 1900rpm on the lug curve. At this operating point there is a 5.7% improvement in BSFC.

The constraints used for matching the original lug curve were keeping peak cylinder pressure below 155 bar, as well as limiting GT-POWER estimated peak cylinder temperature to either 1800 K or the estimated temperature for the stock points, whichever was lower. The low RPM stock points have low AF ratios, which results in cylinder temperatures well over 1800 K, while the higher RPM points had lower peak temperatures. Allowing the peak cylinder temperature to rise to 1800 K for all of the superturbo points could provide additional gains in efficiency for the mid-RPM points, especially at 1600 RPM, as this had the lowest stock cylinder temperature

To optimize under these constraints, we allowed AF ratio and fuel injection timing to change. For the low RPM points, we utilized the supercharging function of the SuperTurbo to provide more air flow, and higher AF ratios. Even though this requires power from the crankshaft, it resulted in efficiency gains, as part is recovered through the turbine, and peak cylinder pressures rise (although still well below the maximum allowable), resulting in greater indicated efficiency within the cylinders. This also should reduce soot emissions, and brings the peak cylinder temperature down significantly, so the limit we imposed of about 1800K was not difficult to obtain. For the higher RPM points, AF ratio stayed about at the stock levels, but with the efficiency gains from turbo compounding, this resulted in slightly lower charge flows and thus slightly lower peak cylinder pressures and temperatures, so we were able to advance the injection timing for these cases, for additional gains in efficiency. By increasing the allowed maximum cylinder temperature for the mid range cases, a drop in air fuel ratio would be possible, as well as further advanced injection timing, so additional gains in efficiency could be realized.

Tables 1, 2 and 3 show the basic relationship between full load efficiency, SuperTurbo function (power contribution) and air fuel ratio. Tables 4, 5 and 6 show the same relationships as they apply to part load conditions which were identified as important to the overall program.

BSFC (g/kWh)	900 RPM	1200 RPM	1600 RPM	1900 RPM	2300 RPM
Stock	200.3	207.3	209.6	206.5	222.2
SuperTurbo	192.5	190.6	198.3	194.8	206.7
% Change	-3.9%	-8.1%	-5.4%	-5.7%	-7.0%

Table1: Full load BSFC comparison

Superturbo Power (kW)	900 RPM	1200 RPM	1600 RPM	1900 RPM	2300 RPM
Superturbo	-7.8	-0.1	27.1	40	42.9

Table 2: Full load SuperTurbo power

Air Fuel Ratio	900 RPM	1200 RPM	1600 RPM	1900 RPM	2300 RPM
Stock	21.2	23	29.7	28	28
Superturbo	29.1	28.7	30	27.7	28.5

Table 3: Full load air fuel ratio

BSFC (g/kWh)	900 RPM 50%	1200 RPM 70%	1600 RPM 70%	1600 RPM 50%	1900 RPM 85%
Stock	194.1	197.8	199.3	205.7	210.4
SuperTurbo	191.2	192.2	186.2	190.3	192.4
% Change	-1.5%	-2.8%	-6.6%	-7.5%	-8.6%

Table 4: Part load BSFC comparison

Superturbo Power (kW)	900 RPM 50%	1200 RPM 70%	1600 RPM 70%	1600 RPM 50%	1900 RPM 85%
Superturbo	-1.1	-1.2	7.7	4.7	14.8

Table 5: Part load SuperTurbo power

Air Fuel Ratio	900 RPM 50%	1200 RPM 70%	1600 RPM 70%	1600 RPM 50%	1900 RPM 85%
Stock	32.4	25.8	32.9	32.7	30.4
Superturbo	36	31.3	36.1	38.1	33

Table 6: Part load air fuel ratio

Figure 7 shows a modeled full load transient at 1200 RPM. The blue line is the stock engine with the standard turbocharger. The green line is the result with a SuperTurbocharger. The engine equiped with the SuperTurbocharger reaches higher BMEP and thus higher power levels faster and can achieve higher total levels. Air to fuel ratio is included to assist in visualizing the modeling approach.

The transient speed is dependant on how steep the compressor acceleration rate can be set. Knowing the full system intertia is key to understanding the torque requirements internal to the SuperTurbo and also the torque being transferred from the engine. When modeling and then running transients, the goal is to never have a reduction in overall engine torque during the ramp up. The allowable accelaration rate is identified during the modeling phase and the associated ramp rates and system torques translate to both the control system development and the hardware design.

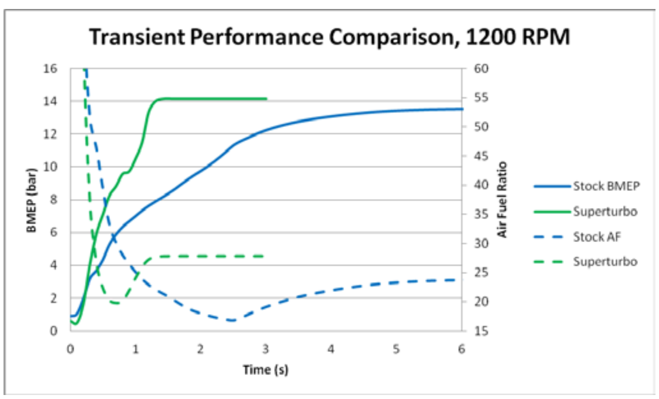

Figure 7: Transient performance comparison

Additional Available Engine Power

During the course of modeling the C18 engine, VanDyne found that the engine was capable of higher power levels than the Army is using it for. The Army has a single turbo 700hp version of this engine. Likely this power level was chosen based on expected life and durability of the engine (and reduced cost and maintenance). There is a twin turbo generator version of this engine that achieves 800hp and a marine version of the engine capable of over 900hp. Should the Army desire, VanDyne can make available that additional power without any hardware addition other than the SuperTurbocharger. This capability can be added by control algorithms for the SuperTurbo controller and ECU. The Army can give the operator temporary access to this higher lug curve or emergency power level. In combat situations this power could be useful in quick evasion, on steep grades or when the vehicle becomes stuck.

The tables below outline the available lug curves in torque and power. Additionally the BSFC improvement of the SuperTurbocharger is still evident.

Power (kW)	900 RPM	1200 RPM	1600 RPM	1900 RPM	2300 RPM
Stock Lug	165	260	440	520	485
SuperTurbo Lug Match	165	260	440	520	485
SuperTurbo High Lug	230	385	580	620	590
SuperTurbo Emergency	255	440	610	690	700

Table 7: Available additional engine power

BSFC (g/kWh)	900 RPM	1200 RPM	1600 RPM	1900 RPM	2300 RPM
Stock Lug	200.3	207.3	209.6	206.5	222.2
Superturbo Lug Match	189.3	189.3	197.5	192.6	203.9
Superturbo High Lug	196.5	192.7	198.7	202.9	204.3
Superturbo Emergency	194.3	185.3	188.3	194.5	199.8

Table 8: Higher power level BSFC

Power (kW)	900 RPM	1200 RPM	1600 RPM	1900 RPM	2300 RPM
Stock Lug	-	-	-	-	-
Superturbo Lug Match	-7.8	-0.1	27.1	40	42.9
Superturbo High Lug	-30.3	4.1	58.7	66.5	56.9
Superturbo Emergency	-7.8	5.3	54.8	75.4	83.4

Table 9: Higher power level SuperTurbo power

Air Fuel Ratio	900 RPM	1200 RPM	1600 RPM	1900 RPM	2300 RPM
Stock Lug	21.2	23	29.7	28	28
Superturbo Lug Match	29.1	28.7	30	27.7	28.5
Superturbo High Lug	29.7	26.1	23	23.8	25.4
Superturbo Emergency	22.1	24.2	22	21.5	20.9

Table 10: Higher power level air fuel ratio

The high lug curve is the estimate of what the engine could produce, instead of limiting load to the stock lug curve. The constraints for this data are again a peak cylinder pressure of about 155 bar, and allowing the maximum cylinder temperature to rise to about 1800 K for all RPMs. Again, supercharging at low RPMs to increase the AF ratio, run the compressor in a more efficient range, and increase cylinder pressure resulted in the best efficiency, as the maximum cylinder pressure was able to rise significantly before reaching the imposed limit. The 1200 RPM case could potentially reach an even higher load, as the cylinder pressure was still not at the limit, but more information about the fueling characteristics of the engine is needed to make such a large change in operating conditions, and still have a reasonably accurate model.

For the higher RPM points, the peak cylinder pressures were already at or close to the 155 bar limit, so the AF ratios decreased to stay within this limit. Additional soot produced at these points could be captured by the DPF. Total air flow remained approximately at the stock engine lug curve values, but with increased fueling. Injection timing was also tuned to provide an optimal operating condition. These decreased AF ratios resulted in the higher allowed cylinder temperatures. Maximum power reached 830 hp at 1900 RPM, up from 700 hp stock, so even with allowances for the actual engine not reaching the same performance levels as the model, an increase to 800 hp should be possible. At this point, the SuperTurbo in the model is producing an extra 66 kW (or 88 hp) through turbo-compounding, which is over half of the indicated gain in power.

This is an estimated lug curve that could be utilized for short periods of time during emergency situations. Allowable peak cylinder pressure is raised to 170 bar, and the peak cylinder temperature limit is eliminated, so the intention is that the engine is not run at these power levels except for extreme circumstances to prevent engine damage and maintain durability. With no limit on the cylinder temperature, AF ratios are further reduced, allowing for additional fueling. Power is increase to over 900 hp at 1900-2300 rpm, with over 100 hp from turbocompounding at 2300 rpm, which indicates that a power level of 900 hp is possible to attain.

Information such as fueling requirements are not available at this time to help validate the model, but this curve should be taken as a guide for the power levels that may be possible if the engine is pushed entirely to its limit.

SUMMARY

a. Superior exhaust energy recovery via a special custom turbine of the SuperTurbocharger.
b. Transmitting this energy to the crankshaft using a proprietary infinitely variable step down.
c. Providing a quick compressor boost from the same transmission to reduce turbo lag.
d. Maximizing the recovery of enhanced heat using the SuperTurbocharger turbine.
e. Improving the fuel efficiency 4% to 8% over a stock turbocharged engine.
f. Simultaneously reducing the soot, CO_2 and hydrocarbon emissions.

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